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Applying Multi-Frequency AC LOCO for Finding Sextupole Errors

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Abstract

A fast and precise technique of multi-frequency AC LOCO has been developed and tested for finding the sextupole alignment and field-offset errors at NSLS-II. This technique is based on sine-wave beam excitation simultaneously at multiple frequencies via different fast correctors. The unique combination of the fast speed and high measurement accuracy opens the door for two different types of potential applications: finding the sextupole alignment and field-offset errors. Beam excitation via fast correctors results in the elimination of the systematic error caused by the hysteresis effect. Systematic errors of the sextupole alignment caused by orbit drift and power supply calibration are also eliminated because the measurement takes only two minutes and does not depend on the current-to-field conversion of sextupole magnets. Furthermore, the simulation studies indicate that multi-frequency AC LOCO together with an orbit bump bigger than 0.5 mm can be applied to measure the relative field offset of a sextupole magnet with a precision better than 10%. The measurement technique is described and the results of two proof-of-principle experiments carried out at NSLS-II are presented.

Introduction

NSLS-II is a third-generation light source with low emittance [1]. The 3-GeV electron storage ring was designed and built with very tight magnet tolerances required to create a lattice providing a large enough dynamic aperture for reliable injection and capture of the beam. At such low emittance, small magnet errors will have relatively large effects on the beam emittances via orbit distortions and field-offsets. The alignment tolerances are 30 μm offset from magnet to magnet and 0.2 mrad in roll angle. A vibrating wire measurement was employed to achieve 5-10 μm resolution of finding the magnetic center. Afterward, magnets were locked onto the girder then installed in the tunnel. Also, the tolerances of the sextupole field offset are required to be better than a few percent in terms of the normalized sextupole strength $K_2 = \frac{1}{BR}\frac{\partial^2 B_y}{\partial x^2}$.

Since the NSLS-II commissioning, a great effort of minimizing the x-y coupling of beam motion was made to achieve the diffraction-limited vertical emittance of $(10^{-10}/4\pi)$ m. Coupling terms in multipole magnets result from the rolls of quadrupoles and vertical offsets of sextupoles. The ring re-alignment using a laser tracker sometime makes the coupling worse. Therefore, beam-based alignment (BBA) techniques are required to make in-situ measurements of the magnetic centers of magnets. A commonly used BBA technique is to calibrate the beam position monitors (BPMs) to the centers of quadrupoles [2]. Varying the quadrupole strength deflects the beam that doesn't pass through the center of the magnet. A different approach based on the Linear Optics from Closed Orbits (LOCO) analysis can potentially calibrate BPMs to the centers of sextupoles

[3]. However, the main disadvantage of the LOCO technique is that it takes a long time for the measurement varying from 10 up to 100 min depending on the machine size. If the LOCO technique is applied to find the sextupole alignment error, a minimum of three sets of orbit response matrices (ORMs) are required by the data analysis [4]. As a result, LOCO suffers from systematic errors caused by slow drifts of the machine parameters during the measurement, as well as by hysteresis effects of adiabatic variations of the orbit corrector magnets. Furthermore, LOCO simulation indicates the measurement precision of 0.1 μm is required to meet the 30 μm magnet-to-magnet offset for calibration of the BPMs to the centers of sextupoles. The standard LOCO technique does not satisfy this requirement. Thanks to the multi-frequency AC LOCO, named MF-AC LOCO, recently developed at NSLS-II [5], its unique combination of high speed and high precision makes the sextupole alignment possible. The MF-AC LOCO was tested at NSLS-II and the result of the calibration of BPMs to sextupole centers is presented in this paper. Furthermore, the proof-of-principle experiment indicates the MF-AC LOCO together with a 0.6 mm orbit bump can measure the relative field offset (ΔK_2) of a sextupole magnet with a precision better than 10%.

Description of the Method

Alignment Error

If the beam orbit goes off-center in a sextupole with the normalized strength $k_2 = \frac{e}{c \cdot p} \cdot \frac{\partial^2 B_y}{\partial x^2}$, the following normal quadrupole and skew-quadrupole components are generated [4]:

$$k1_{\text{quad}} = x \cdot k_2,$$
$$k1_{\text{skew}} = -y \cdot k_2, \tag{1}$$

where x and y are the horizontal and vertical orbit offsets inside the sextupole, respectively. If the normal quadrupole and skew quadrupole errors vary as a function of the sextupole strength, the slopes of the functions (1) give the horizontal and vertical orbit offsets in the sextupole.

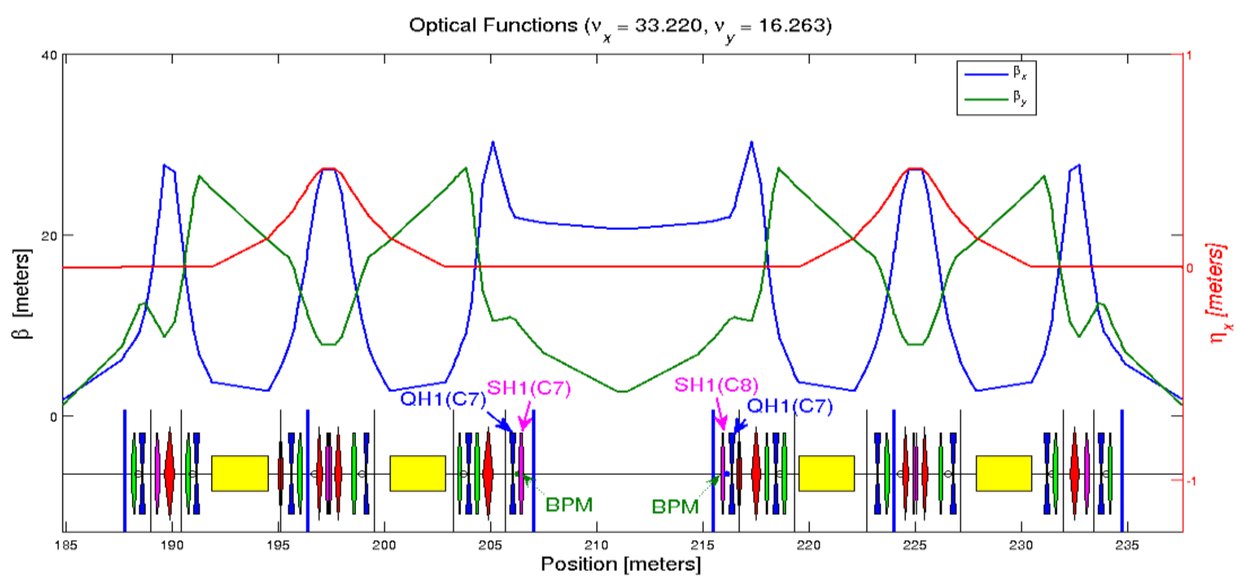

Fig. 1 Beta functions and dispersion (top) and the machine elements (bottom) in one super-period of NSLS-II. In the bottom, positions of the sextupoles and BPMs involving in the BBA measurement are indicated by magenta arrow lines with labels ‘SH1(C7)’ and ‘SH1(C8)’ and green arrow lines with label ‘BPM’ respectively.

To benefit from the high speed and high precision of the MF-AC LOCO technique, it is important to have the measurement procedure independent of the current-to-field conversion of the sextupole power supply. In this case, no error results from the k_2 calibration. The sextupole strength k_2 varies linearly with the power supply current to calculate the slope accurately, and the orbit is recorded for each LOCO data set to minimize the quadrupole and skew quadrupole errors introduced by the orbit variation during the measurement. We performed a scan of two SH1 sextupoles (Fig. 1), which share the same power supply. The strength of 0%, 30%, and 60% of the operational setting was set and the ORM was measured at each point via MF-AC LOCO. The scan range away from the magnet saturation was chosen to guarantee the linearity. The measurement takes six minutes including three sets of ORMs, beam orbits, and dispersions. Here, (x_0, y_0), (x_1, y_1), and (x_2, y_2) are the horizontal and vertical beam orbits at those three scan points; after subtracting the horizontal x_r and vertical $y_r$coordinate of the sextupole center from those orbits, they become the horizontal and vertical orbit offsets inside the sextupole. Whenever the sextupole setting is varied, the orbit correction should be applied to maintain the same orbit. Ideally, these orbits should be the same; in reality, they are slightly different due to the limitation of orbit correction, ground motion, fluctuations of magnet power supplies, etc. The fitted lattice from the LOCO analysis of the first scan point is used as the reference lattice for the rest of the data analysis. Equations (2a) and (2b) are the skew quadrupole components corresponding to the 2nd and 3rd scan points. Here y_r is the vertical offset of the sextupole with respect to the BPM and this is the BBA we are looking for. Dividing equation (2a) by equation (2b) arrives at equation (3). Here, $A = \frac{2 \cdot k1_{\text{skew},1}}{k1_{\text{skew},2}}$; $k1_{\text{skew},1}$ and $k1_{\text{skew},2}$ are the LOCO-fitted skew quadrupole components in the sextupole at the 2nd and 3rd scan points.

It is clear the BBA of the sextupole (3) is independent of the sextupole power supply calibration and the orbit variation during the measurement is mostly compensated. It is similar for the horizontal orbit offset of the sextupole, which is obtained by replacing y with x and $k1_{\text{skew}}$ with $k1_{\text{quad}}$ in equations (2a), (2b), and (3).

$$k1_{\text{skew},1} = -(y_1 - y_r) \cdot k_2 \cdot 0.3, \tag{2a}$$

$$k1_{\text{skew},2} = -(y_2 - y_r) \cdot k_2 \cdot 0.6, \tag{2b}$$

$$y_r = \frac{A \cdot y_2 - y_1}{A - 1}, \tag{3}$$

To correctly analyze the ORM, the sextupole has to include three components: the sextupole component itself (not required for the ORM fit but improves the fit accuracy because the nonlinear sextupole fields exist in the measurement), the quadrupole component to represent the horizontal displacement of the sextupole, and the skew quadrupole component to represent the vertical displacement of the sextupole. For the sextupoles not involved in the alignment process, their quadrupole and skew quadrupole components are not fit in the LOCO analysis. A standard LOCO analysis is applied to the first scan point to obtain the fitted machine lattice, which is used as the reference lattice for the rest scan points. Two pairs of quadrupole and skew quadrupole components $k1_{\text{quad}}$ and $k1_{\text{skew}}$ belonging to the sextupole misalignment, are added to the fitting parameters. The horizontal and vertical offsets (BBA) of these two sextupoles are obtained from equation (3).

Relative Field-offset Error

The simulation study indicates that MF-AC LOCO can measure the relative change of sextupole strength ΔK_2 reasonably well, with a precision better than 10% of its nominal value; however, the measurement is not reliable in determining the absolute value K_2 (with an error as large as 20% or more) due to the intrinsic problem of LOCO degeneracies among different fitting

parameters [6].
The step-by-step procedure for measuring the relative field offset of sextupole:

1. Turn off SH3 and SH4 in Cell08
2. Set up a local bump with $\Delta x \geq 0.5$ mm via user orbit offset
3. Set up MF-AC LOCO with 30 different frequencies
4. Set up the result of MF-AC LOCO as the reference
5. Reduce SH1 in Cell08 with a step of 10%
   a. Repeat MF-AC LOCO with 'FitParameters' limited to SH1 in Cell08
   b. Update the result as the new reference
6. Repeat step 5 till SH1 is reduced to 50% of the initial nominal value

Taken the local bump in cell08 into consideration, the MF-AC LOCO analysis (1) is applied to calibrate the field offset of sextupole SH1. This calibration is obtained from the relationship $\Delta K_{analys} = b \cdot \Delta K_{LOCO}$. Here ΔK_{analys} is the analysis based on equation (1) and ΔK_{LOCO} is the measurement of MF-AC LOCO. The reason why we can perform such analysis is that the LOCO algorithm has significantly better precision for the relative change of a fitting parameter among different data sets compared to the absolute value of the fitting parameter.

Experimental Results

Alignment Error

The MF-AC LOCO excitation frequencies are 20 Hz, 22 Hz, …, 78 Hz [5]; the spectra of the horizontal and vertical BPM signals are shown in Fig. 2. Since this is the final configuration, which will be routinely used at the NSLS-II storage ring as the linear lattice tool, some efforts are spent in characterizing its performance.

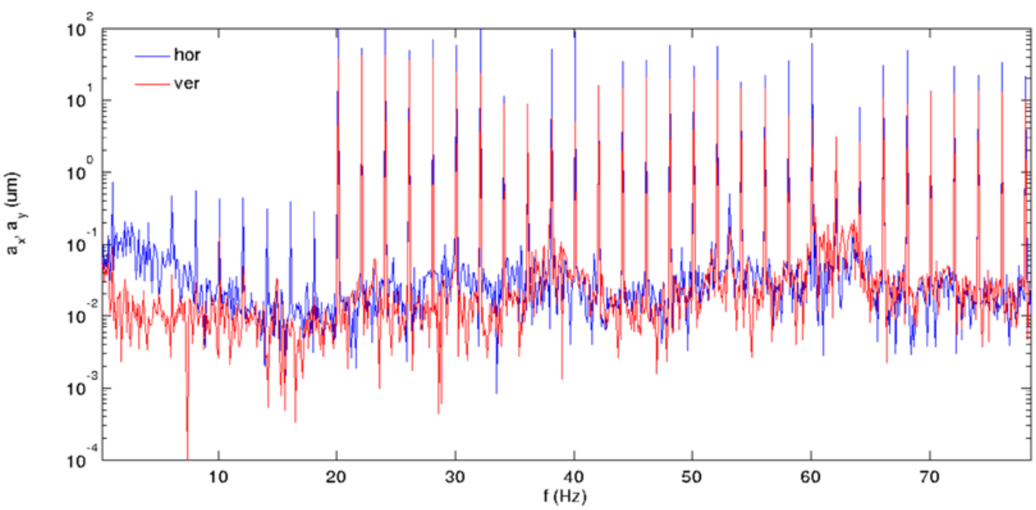

Fig. 2 Amplitude spectra of horizontal (blue) and vertical (red) BPM signals.

We repeated the same measurement 10 times in both horizontal and vertical directions to estimate the statistical errors. For each set of the data $j = 1 \ldots 10$, averaging all BPMs' response to every excitation frequency f_i $(i = 1 \ldots 30)$, we obtain $\langle a(f_i) \rangle_j$. The RMS deviation of those 10 data sets at each excitation frequency fi gives the BPM resolution at fi. In the measurement, we keep the slow orbit feedback on to minimize the slow beam motion. In the excitation frequency range from

20 Hz to 78 Hz, the measured errors are less than 30 nm. In the 30-frequency excitation mode, we achieved the BPM resolution similar to the single-frequency mode.

Examples of the horizontal (left) and vertical (right) oscillation amplitudes at one of those 30 excitation frequencies measured by all BPMs, which corresponds to one column of the ORM (a single corrector), are presented in Fig. 3. Different colors represent the ten repeated measurements. For the MF-AC LOCO measurement, 90 horizontal and 90 vertical fast orbit correctors installed for the fast orbit feedback are used. By repeating the measurement six times for different fast correctors in the 30-frequency excitation mode, a complete set of the ORM is measured in less than 2 min. Since the achieved 30 nm precision and 2 min measurement time already meet the sextupole alignment criteria based on our simulations, we carried out the proof-of-principle experiment at NSLS-II to test the above-described method of MF-AC LOCO measurement of the sextupole alignment error.

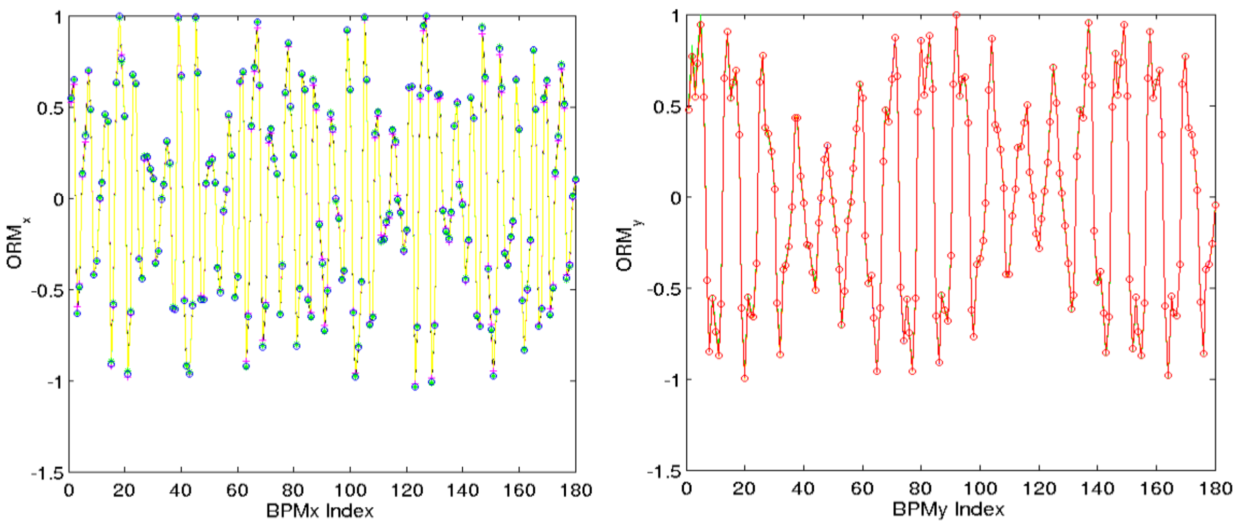

Fig. 3 Amplitudes measured by all BPMs at 20 Hz: horizontal (left) and vertical (right). Different colors represent the ten repeated measurements.

Three complete sets of ORMs, dispersions, and beam orbits are recorded at three different cases when SH1 sextupoles in Cell07 and Cell08 are set to 0%, 30%, and 60% of their nominal settings. We analyze these three LOCO data sets according to the steps described above. The measured sextupole alignment errors are shown in Table I. For comparison, the BBA values of their adjacent QH1 quadrupoles (Fig. 1) obtained from the conventional quadrupole scan method are also listed in the table. The errors of the sextupole alignment measured by the MF-AC LOCO method are estimated from the simulation with the input of the measurement precision and the orbit variation during the measurement. The errors of the quadrupole scan method are estimated by the RMS deviation of five repeated measurements.

	SH1(C7)	SH1(C8)	QH1(C7)	QH1(C8)
X offset (μm)	36.3 (+/-14.4)	59.7 (+/-15.1)	64.16 (+/-24.6)	46.0 (+/-56.3)
Y offset (μm)	64.8 (+/-2.7)	6.7 (+/-7.9)	64.7 (+/-12.9)	-15.1 (+/-41.4)

Table I. BBA of the sextupoles via MF-AC LOCO and BBA of their adjacent quadrupoles via quadrupole scan method.

Relative Field-offset Error

The number of different excitation frequencies of MF-AC LOCO, which can be simultaneously applied to different fast correctors, is limited to 30 by the cell-controller configuration in the NSLS-II control system. Two sets of low- and high-frequency options, taking the power supply slew rate into consideration and simultaneously avoiding the resonant frequencies, are shown in Fig. 4. These settings are different from the first experiment of the sextupole alignment. Carefully avoiding all possible resonances, the frequency spacing can be reduced from 2 Hz down to 1Hz with the gain of larger excitation amplitude in the low-frequency option providing a better signal-to-noise ratio. Furthermore, we can extend the option to the high-frequency range which might be needed in some special cases. The green triangles and red circles represent the low- and high-frequency cases, respectively.

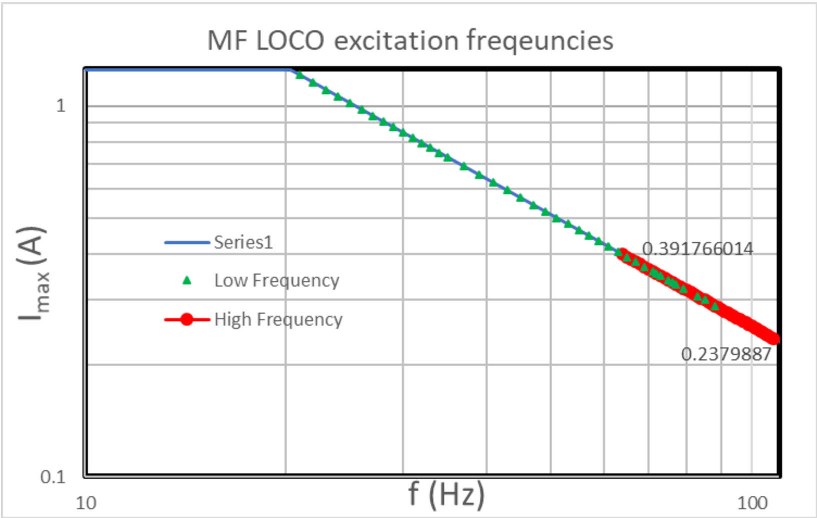

Fig. 4. The green triangles and red circles represent the low- and high-frequency options, respectively. Above 20Hz, the maximum excitation current $I_{\max}$ decreases with the frequency f.

Examples of low-frequency and high-frequency spectra of the beam oscillation measured by BPMs during 10 s with 10 kHz sampling frequency are shown as the left and right plots in Fig. 5, respectively.

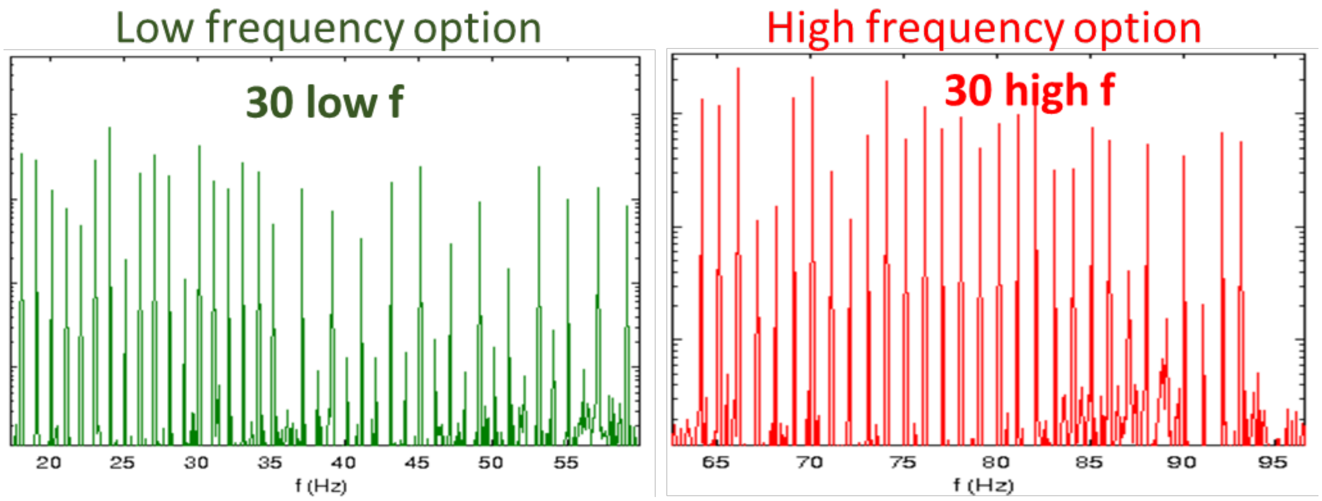

Fig. 5. Low-frequency (left) and high-frequency (right) spectra from the BPM 10s FA data.

We follow the procedure described in the Method section: turn off SH3 and SH4 in Cell08; set up a local bump with $\Delta x = 0.6$ mm; apply MF-AC LOCO with the low- and high-frequency options at each scale of SH1 in Cell08; apply the analytical calibration via $\Delta K_{analys} = b \cdot \Delta K_{LOCO}$. The results are shown in Fig. 6.

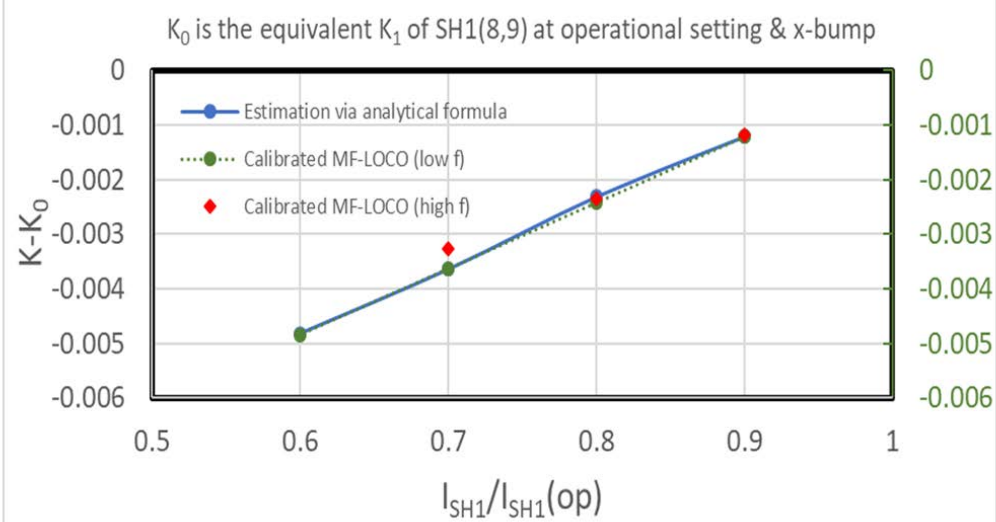

Fig. 6 The variation of the equivalent quadrupole error, referring to the operational SH1 setting, is plotted as a function of the change of sextupole current. MF-AC LOCO low- and high-frequency options are plotted as the green circles and red diamonds, respectively. The blue curve is the analysis based on equation (1).

MF-AC LOCO provides adequate precision to measure the relative change of the sextupole field offset with the accuracy of better than 10% of its nominal value, as it was demonstrated in both low- and high- frequency options. However, due to the intrinsic property of cross-talking among different fitting parameters in the LOCO algorithm, it is impossible to determine the absolute sextupole strength K_2 by the MF-AC LOCO method together with a local bump.

Conclusion

A fast and precise technique of MF-AC LOCO has been developed and tested for finding the sextupole alignment errors at NSLS-II. This technique is based on sine-wave beam excitation simultaneously at multiple frequencies using different fast correctors. By repeating the measurement six times for the total 90 horizontal and 90 vertical fast correctors in the 30-frequency excitation mode, a complete set of the ORM can be measured in less than 2 min. Minimum three sets of the LOCO data with the measurement precision of 0.1 μm are required to meet the specification of 30 μm offset magnet-to-magnet in the BPMs-to-sextupole calibration. The unique combination of the fast speed and high measurement accuracy opens the door for finding the sextupole alignment errors. At NSLS-II, we carried out a proof-of-principle experiment of the 30-frequency excitation of 30 correctors. We were able to keep the measurement accuracy in the nanometer level for all the excitation frequencies in the 20 – 98 Hz range. The BBA results of the sextupole-to-quadrupole offsets indicate that the NSLS-II magnet alignments meet the tight magnet tolerances. In the vertical direction, there is a reasonable agreement between SH1 and QH1 offsets in the same magnet girder; however, the horizontal discrepancies are bigger. Detailed study and further improvement of the sextupole alignment via the MF-AC LOCO method needs more work. Due to the intrinsic limitation of cross-talking among different fitting parameters in LOCO, it is impossible to determine accurately the absolute values of sextupole strength by MF-AC LOCO plus a local bump. A new algorithm should be explored to mitigate the degeneracy problem.

Acknowledgments

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